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Cold-formed stainless steel RHSs/SHSs under combined compression and cyclic bending

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ABSTRACT

This paper discusses the behaviour of stainless steel rectangular and square hollow sections (RHSs and SHSs) under combined constant compression and uniaxial cyclic bending. A total of 10 specimens were tested, covering a variety of section slenderness, axial load ratio, and bending direction. These test parameters were found to have evident influences on the local buckling resistance of the specimens. It was also observed that the current codified classification limits underestimate the ability of the stainless steel sections to develop plastic stresses. Moreover, the specimens exhibited low to moderate levels of ductility and energy dissipation capacity due to a relatively early occurrence of local buckling. A numerical study was subsequently conducted, shedding further light on the strength, stress pattern, ductility, and local failure behaviour of the specimens. A more extensive parametric study was then carried out, which provides basis for the proposal of a ductility-oriented design approach that aims to offer a quick yet reliable evaluation tool for predicting the available ductility supply of stainless steel RHSs/SHSs under different loading conditions. The rationality of the current major design codes for predicting the strength of stainless steel members was also evaluated, and it was found that the design codes tend to be conservative.

1. Introduction

Owing to favourable corrosion resistance, workability, ductility, and aesthetic appearance, stainless steel has now been considered as a viable class of constructional material to cater to both architectural and structural needs. Compared with low carbon steel, stainless steel exhibits a distinctive nonlinear stress-strain relationship with relatively low proportional limit, no strictly defined yield plateau, and evident strain hardening. These properties can result in different behaviours between stainless steel and low carbon steel members. Over the past two decades, extensive investigations have been conducted on stainless steel at material, cross-section and member levels. The applicability of the existing structural steel design principles to stainless steel structures has been carefully revisited, and modifications or new design approaches have been proposed where necessary. A number of early research outcomes have already been included in major stainless steel design codes [1–3], which further promoted widespread applications of this material in buildings and infrastructures, including Louvre Pyramid (France), Millennium footbridge (UK), and Tsing Ma Bridge (Hong Kong) [4].

So far, most of the relevant studies focused on the behaviour of stainless steel members under static loading conditions. At section level, Young and Lui [5] conducted a series of compression tests on stainless steel square and rectangular hollow section (SHS and RHS) stub columns, and it was concluded that the design predictions for section capacity are generally conservative. Gardner and Nethercot [6] carried out 37 more tests on such columns, based on which a new design approach was proposed. Bardi and Kyriakides [7] examined a number of stainless steel circular hollow sections (CHSs), where the focus was given to the inelastic local buckling behaviour. Zhou et al. [8] discussed the interaction effect of constituent plate elements within stainless steel cross-sections, and found that the interaction effect is quite obvious particularly for slender sections. Summarising available test data, design recommendations on stainless steel section classifications were given by Gardner and Theofanous [9].

Apart from the tests and analysis on stub columns, slender stainless steel columns were investigated by Rasmussen and Hancock [10], Young and Liu [11], Liu and Young [12], and Theofanous and Gardner [13]. It was commonly found that the current flexural buckling curve for stainless steel hollow section columns is generally accurate, although for certain column types under specific boundary conditions (e.g. fixed-ended cold-formed stainless steel RHS/SHS columns), the design capacities predicted by the American and European codes [1–2] can be less reliable than those predicted by the Australian/New Zealand Standard [3].

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It is noted that most of these investigations also involved stub column tests for comparison purposes, which largely enriched the test data pool for the evaluation of the section behaviour. In parallel with the studies on columns, a series of three and four point bending tests have been conducted on stainless steel RHS/SHS beams to understand their moment-curvature relationships [14–16]. Recent research interests have also been extended to the behaviour of stainless steel beam-columns which were compressed with varying loading eccentricities [17–22]. A common finding was that the current design approaches are reasonably safe, although some shortcomings related to inaccurate interaction factors have been identified. In light of this, modifications to the existing design rules were proposed [23]. Furthermore, concrete-filled stainless steel tubular columns, combining the advantages of stainless steel and steel-concrete composite action, have attracted great attention [24–28]. The cross-section and member responses of the composite columns under ambient and elevated temperature scenarios were covered in these studies.

The literature shows that a series of studies have been conducted on stainless steel members under monotonic static loading scenarios; however, information on their seismic performance is rare, which hinders a confident use of stainless steel members in seismic-active regions. In particular, when stainless steel is employed for columns, the cyclic performance of the column sections under combined compression and cyclic bending is of fundamental importance to structural engineers. Although some studies have been carried out to understand the basic material properties of stainless steel under cyclic loading [29–30], the investigations at section and member levels is generally inadequate. In light of this, the current study aims to investigate the structural behaviour of stainless steel RHSs/SHSs under cyclic loading. The research commences with an experimental study covering a various combination of section dimensions and loading scenarios. A numerical study is subsequently conducted, shedding further light on the strength, ductility, and local failure behaviour of the considered specimens. The calibrated models enable a further parametric study to be conducted taking account of a wider range of parameter matrix, and based on the available data, the codified prediction of the strength of stainless steel RHS/SHS beam-columns is commented, and a ductility-oriented design approach for these sections under seismic conditions is finally proposed.

2. Experimental program

2.1. Test specimens

A total of 10 cold-formed stainless steel tubular section specimens were tested under constant axial load and cyclically increased uniaxial bending, as illustrated in Fig. 1. These specimens were designed as stub columns with a nominal total length (L) of 660 mm, such that overall flexural buckling can be avoided whereas local failure modes govern. The tubes were cold-rolled from Grade 304 Austenite stainless steel plates to form the desired RHS/SHS shape at room temperature and were finished by longitudinal welding. The tubes were then cut and machined to the required length. Two Q345 (nominal yield strength = 345 MPa) steel endplates with a thickness of 20 mm were welded to the two ends of each specimen, and additional stiffeners were used to strengthen the column ends. The height of each stiffener was 80 mm, leading to a reduced effective length of 500 mm for the stub columns.

The main test parameters were section dimension, axial load ratio, and bending direction. Three different section sizes were selected, namely, SHS 120 × 120 × 3, RHS 120 × 60 × 3, and RHS 120 × 60 × 2, which are abbreviated as S1, R1, and R2 sections, respectively. Details of the specimens are provided in Fig. 1 with the measured dimensions given in Table 1. The definition of the symbols for the section is marked in the figure, where b and h are the overall width of the web and that of the flange, respectively; b_p and h_p are the corresponding widths excluding the rounded corners; t is the thickness of the tube, r_0 is the outer radius of the arc corner, and V shows the loading/bending direction. Since local buckling is the main concern of the current study, relatively slender sections were selected for the specimens. The measured width-to-thickness ratios, i.e., $r_f = h_p/\varepsilon t$ and $r_w = b_p/\varepsilon t$, ranged from 24.7 to 85.4, where $\varepsilon = (235E_0/210000\sigma_{0.2})^{0.5}$, in which E_0 is the measured Young's modulus, and $\sigma_{0.2}$ is the measured yield strength (0.2% proof stress) of the flat part, as elaborated later. Two different levels of axial load ratio (n) were considered in the tests, i.e., $n = 0.2$ and $n = 0.4$, where $n = P/\sigma_{0.2}A$, in which P is the applied constant axial load, and A is the measured cross-sectional area. Both strong-axis and weak-axis bending scenarios were considered for the specimens. For ease of reference, each specimen was designated with a specimen code,

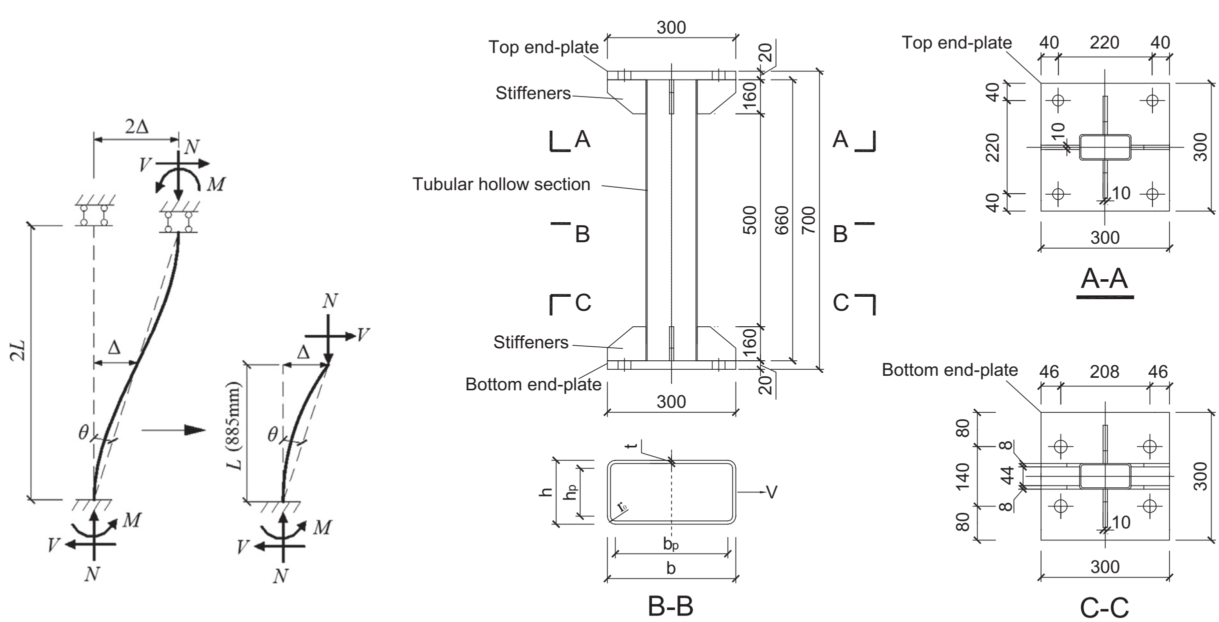

Fig. 1. Details of test specimens.